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AUTHOR(S):

Jido, Daisuke; Kanada-En'yo, Yoshiko

CITATION:

Jido, Daisuke ...[et al]. Baryon resonances as hadronic molecule states with kaons. Hyperfine Interactions 2009, 193(1-3): 253-259

ISSUE DATE:

2009-09

URL:

http://hdl.handle.net/2433/109964

Noname manuscript No.
(will be inserted by the editor)

Baryon resonances as hadronic molecule states with kaons

Daisuke Jido · Yoshiko Kanada-En'yo

Received: date / Accepted: date

Abstract We investigate hadronic molecule states of $K\bar{K}N$ and $\bar{K}\bar{K}N$ systems with $I = 1/2$ and $J^P = 1/2^+$, assuming that $\Lambda(1405)$ and the scalar mesons, $f_0(980)$, $a_0(980)$, are reproduced as quasi-bound states of $\bar{K}N$ and $K\bar{K}$. Performing non-relativistic three-body calculations for these systems, we find weakly bound states for $K\bar{K}N$ and $\bar{K}\bar{K}N$ around 1900 MeV, which correspond to new baryon resonances of N^* and Ξ^* with $J^P = 1/2^+$. We find that these resonances have cluster structure of the two-body bound state keeping its properties as in the isolated two-particle system.

Keywords three-body bound state · $\Lambda(1405)$ resonance · kaon-nucleon interaction

PACS 14.20.Gk · 13.75.Jz · 13.30.Eg · 21.45.-v

1 Introduction

The study of hadron structure is one of the most important issues in hadron physics. Recent interest in this line is developed in exploring quasi-bound systems of mesons and baryons governed by strong interactions among the hadrons. One of the long-standing candidates is the $\Lambda(1405)$ resonance considered as a quasi-bound state of $\bar{K}N$ system [1]. It has been also suggested that the $f_0(980)$ and $a_0(980)$ scalar mesons are molecular states of $K\bar{K}$ [2]. In such multi-hadron systems, anti-kaon plays a unique role due to its heavy mass and Nambu-Goldstone boson nature. The heavier kaon mass indicates stronger s-wave interactions around the threshold than those for pion according to chiral effective theory. In addition, realizing that typical kaon kinetic energy in the bound system estimated by range of hadronic interaction is small in comparison with the kaon mass, one may treat kaons in multi-hadron systems in many-body formulations. The strong attraction in the $\bar{K}N$ system led to the idea of deeply bound

D. Jido
Yukawa Institute for Theoretical Physics, Kyoto University, Sakyo, Kyoto 606-8520, Japan
Tel.: +81-75-753-7034
Fax: +81-75-753-7010
E-mail: jido@yukawa.kyoto-u.ac.jp

Y. Kanada-En'yo
Yukawa Institute for Theoretical Physics, Kyoto University, Sakyo, Kyoto 606-8520, Japan

kaonic states in light nuclei, such as K^-pp and K^-ppn, pointed out by Akaishi and Yamazaki [3]. Later, many theoretical studies on the structure of the K^-pp system have been done, having turned out that the K^-pp system is bound with a large width [4].

One of the key issues for study of the $\bar{K}N$ interaction is subthreshold properties of the $\bar{K}N$ scattering amplitude, namely the resonance position of $\Lambda(1405)$. Particle Data Group reports the mass of the $\Lambda(1405)$ resonance around 1405 MeV, which is extracted mainly in the $\pi\Sigma$ final state interaction. Based on this fact, a phenomenological effective $\bar{K}N$ potential (AY potential) was derived in Refs. [3,5], having relatively strong attraction in the $I=0$ channel to provide the K^-p bound state at 1405 MeV. Recent theoretical studies of $\Lambda(1405)$ in coupled channels approach with chiral dynamics have indicated that $\Lambda(1405)$ is described as a superposition of two pole states and one of the states is considered to be a $\bar{K}N$ quasibound state embedded in strongly interacting $\pi\Sigma$ continuum [6–8]. This double-pole conjecture suggests that the resonance position in the $\bar{K}N$ scattering amplitudes with $I=0$ is around 1420 MeV, which is higher than the energy position of the nominal $\Lambda(1405)$ resonance. Based on this chiral SU(3) coupled-channel dynamics, Hyodo and Weise have derived another effective $\bar{K}N$ potential (HW potential) [7]. The HW potential provides a $\bar{K}N$ quasibound state at $\sim$ 1420 MeV instead of 1405 MeV, and is not as strong as the AY potential.

Common achievement of these studies on the s-wave $\bar{K}N$ effective potential is that $\bar{K}N$ interaction with $I=0$ is strongly attractive and develops a quasibound state somewhere around the $\Lambda(1405)$ resonance. Starting from these strong $\bar{K}N$ interactions together with $\bar{K}K$ quasibound picture of $f_0(980)$ and $a_0(980)$, we examine possible bound states of the lightest two-kaon nuclear systems $K\bar{K}N$ and $\bar{K}\bar{K}N$ with $I=1/2$ and $J^P=1/2^+$, in hadronic molecule picture. The details can be found in Refs. [9,10].

2 Formulation

We apply a non-relativistic three-body potential model for the $K\bar{K}N$ and $\bar{K}\bar{K}N$ systems. First we investigate the $K\bar{K}N$ system, then later we briefly comment on the $\bar{K}\bar{K}N$ state. The Hamiltonian for the $K\bar{K}N$ system is given by

$$H = T + V \tag{1}$$

$$V \equiv V_{\bar{K}N}(r_1) + V_{KN}(r_2) + V_{K\bar{K}}(r_3), \tag{2}$$

with the kinetic energy T and the potential energy V which consists of effective two-body interactions given in ℓ-independent local potential form as functions of $\bar{K}$-N, K-N and K-$\bar{K}$ distances. We assume isospin symmetry in the effective interactions, and we also use isospin-averaged masses, $M_K = 495.7$ MeV and $M_N = 938.9$ MeV. We do not consider three-body forces nor transitions to two-hadron decays, which will be important if the constituent hadrons are localized in a small region.

The effective interactions are given by complex-valued functions to implement open channels, ($\pi\Lambda$, $\pi\Sigma$) for $\bar{K}N$ and ($\pi\pi$, $\pi\eta$) for $K\bar{K}$. In solving Schrödinger equation for $K\bar{K}N$, we first take only the real part of the potentials and obtain wavefunctions in a variational approach with Gaussian expansion method for the three-body system [11]. With the wavefunctions, we calculate bound state energies E as expectation values of the total Hamiltonian (1). The widths of the bound states are evaluated by the imaginary part of the complex energies as $\Gamma = -2\,\mathrm{Im}E$.

Table 1 The interaction parameters and the properties of two-body systems. The energies (E) are evaluated from the corresponding two-body threshold. We also list the root-mean-square two-body distances of the $\bar{K}N(I=0)$, $K\bar{K}(I=0)$ and $K\bar{K}(I=1)$ states, which correspond to $\Lambda(1405)$ and $f_0(980), a_0(980)$, respectively. For the $K\bar{K}$ interactions, we show the scattering lengths obtained in the present parameters.

	parameter set of interactions	
	(A)	(B)
b (fm)	0.47	0.66
$\bar{K}N$	HW-HNJH	AY
$U^{I=0}_{\bar{K}N}$ (MeV)	$-908-181i$	$-595-83i$
$U^{I=1}_{\bar{K}N}$ (MeV)	$-415-170i$	$-175-105i$
$\bar{K}N(I=0)$ state		
ReE (MeV)	-11	-31
ImE (MeV)	-22	-20
$\bar{K}$-N distance (fm)	1.9	1.4
$K\bar{K}$	KK(A)	KK(B)
$U^{I=0,1}_{K\bar{K}}$ (MeV)	$-1155-283i$	$-630-210i$
$K\bar{K}(I=0,1)$ state		
ReE (MeV)	-11	-11
ImE (MeV)	-30	-30
K-$\bar{K}$ distance (fm)	2.1	2.2
KN	KN(A)	KN(B)
$U^{I=0}_{KN}$ (MeV)	0	0
$U^{I=1}_{KN}$ (MeV)	820	231
$a^{I=0}_{KN}$ (fm)	0	0
$a^{I=1}_{KN}$ (fm)	-0.31	-0.31

The effective interactions are parametrized in a one-ragne Gaussian form as

$$V_a(r) = U_a \exp\left[-(r/b)^2\right] \tag{3}$$

with the potential strength U and the range parameter a. The parameters used in this work are summarized in Table 1. The strength of the $\bar{K}N$ potential is fixed by theoretical analyses of the $\Lambda(1405)$ resonance and $\bar{K}N$ scattering. Here we compare two different effective potentials. One is given by Hyodo and Weise in Ref. [7] and was derived based on the chiral unitary approach for s-wave scattering amplitude with strangeness $S=-1$. We use the parameter set referred as HNJH in Ref. [7], which was obtained by the chiral unitary model with the parameters of Ref. [12]. We refer to this potential as "HW-HNJH potential". The other interaction is Akaishi-Yamazaki (AY) potential derived phenomenologically by using analyzed $\bar{K}N$ scattering amplitudes and kaonic hydrogen data, and it reproduces the $\Lambda(1405)$ resonance as a K^-p bound state at 1405 MeV [3,5]. Hereafter we refer to the quasi-bound $\bar{K}N$ state as $\{\bar{K}N\}_{I=0}$. For the interactions of the $\bar{K}K$ systems with $I=0$ and $I=1$, the strengths are determined so as to form quasibound states having the observed masses and widths of $f_0(980)$ and $a_0(980)$. We take the mass 980 MeV and the width 60 MeV as the inputs to determine the $K\bar{K}$ interactions in both the $I=0$ and $I=1$ channels. The repulsive KN interaction is fixed by experimentally obtained scattering lengths: $a^{I=0}_{KN}=-0.035$ fm and $a^{I=1}_{KN}=-0.310\pm0.003$ fm [13]. For the range parameters of the $\bar{K}K$ and KN potentials we use the same values of the $\bar{K}N$ interaction, $b=0.47$ fm for the HW-HNJH potential and $b=0.66$ fm for the AY potential. Solving two-body problems

Table 2 Energies and spatial structure of the $K\bar{K}N$ states calculated with the parameter sets (A) and (B) given in Table 1. The results without the KN repulsive interaction are also shown. Contributions of $V^{I=0,1}_{\bar{K}N}$ and $V^{I=0,1}_{K\bar{K}}$ to the imaginary energy are separately listed.

parameter set	(A)	(A)	(B)	(B)
$V_{\bar{K}N}$	HW-HNJH	HW-HNJH	AY	AY
V_{KN}	on	off	on	off
ReE	−19	−39	−41	−57
$\langle T\rangle$	169	282	175	227
$\langle \mathrm{Re}V\rangle$	−188	−320	−216	−284
ImE	−44	−72	−49	−63
$\langle \mathrm{Im}V^{I=0}_{\bar{K}N}\rangle$	−17	−30	−19	−23
$\langle \mathrm{Im}V^{I=1}_{\bar{K}N}\rangle$	−1	0	0	0
$\langle \mathrm{Im}V^{I=0}_{K\bar{K}}\rangle$	−1	−10	−4	−10
$\langle \mathrm{Im}V^{I=1}_{K\bar{K}}\rangle$	−25	−31	−25	−31
spatial structure				
$r_{K\bar{K}N}$ (fm)	1.7	1.0	1.4	1.0
$d_{\bar{K}N}$ (fm)	2.1	1.3	1.3	1.2
$d_{K\bar{K}}$ (fm)	2.3	1.4	2.1	1.5
d_{KN} (fm)	2.8	1.6	2.3	1.6

with the attractive potentials shown in Table 1, we find that the kinetic energies in the two-body bound systems are small for nonrelativistic treatments.

3 Results

Let us show the results of investigation of the $K\bar{K}N$ system with $I = 1/2$ and $J^P = 1/2^+$. First of all, as summarized in Table 2, we find that, in both calculations (A) with the HW-HNJH and (B) with the AY potentials, the $K\bar{K}N$ bound state is obtained below all threshold energies of the $\{\bar{K}N\}_{I=0}+K$, $\{K\bar{K}\}_{I=0}+N$ and $\{K\bar{K}\}_{I=1}+N$ channels, which correspond to the $\Lambda(1405) + K$, $f_0(980) + N$ and $a_0(980) + N$ states, respectively. The $K\bar{K}N$ bound state appears about 10 MeV below the lowest two-body threshold, $\{\bar{K}N\}_{I=0}+K$, in both cases (A) and (B). Since this binding energy is compatible with those of nuclear many-body systems, it should be considered as a weak binding energy on the energy scale of hadron systems.

The weakly bound system has the following significant features. The obtained binding energies and widths of the $K\bar{K}N$ state are almost given by the sum of those of $\Lambda(1405)$ and $a_0(980)$ (or $f_0(980)$), respectively. In addition, the present result for the spatial structure of the $K\bar{K}N$ system shows that the r.m.s. $\bar{K}$-N and K-$\bar{K}$ distances in the three-body $K\bar{K}N$ state have values close to those in the quasi-bound two-body states, $\{\bar{K}N\}_{I=0}$ and $\{K\bar{K}\}_{I=0,1}$. This implies that the two subsystems of the three-body state have very similar characters with those in the isolated two-particle systems.

For the isospin configuration of the $K\bar{K}N$ state, we find that the $\bar{K}N$ subsystem has a dominant $I = 0$ component. In the $K\bar{K}$ subsystem, the $I = 1$ configuration is dominant while the $I = 0$ component gives minor contribution. This is because, in both $I = 0$ and $I = 1$ channels, the $K\bar{K}$ attraction is strong enough to provide quasi-bound $K\bar{K}$ states, but the $I = 1$ configuration of $\bar{K}K$ is favorable to have total isospin 1/2 for the $K\bar{K}N$ with the $\{\bar{K}N\}_{I=0}$ subsystem. Due to this isospin configuration,

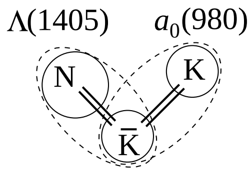

Fig. 1 Schematic structure of the $K\bar{K}N$ bound system.

the $K\bar{K}N$ system has significant decay patterns. The imaginary potentials of the $\bar{K}N$ with $I=0$ and the $K\bar{K}$ with $I=1$ give large contributions as about 40 MeV and 50 MeV, respectively. The former corresponds to the $\Lambda(1405)$ decay channel and gives the $\bar{K}N \to \pi\Sigma$ decay mode with $I=0$. The latter is given by the $a_0(980)$ decay, which is dominated by $K\bar{K} \to \pi\eta$. Therefore, we conclude that the dominant decay modes of the $K\bar{K}N$ state are $\pi\Sigma K$ and $\pi\eta N$ and that decays to $\pi\Lambda K$ and $\pi\pi N$ are suppressed. This is one of the important characters of the $K\bar{K}N$ bound system.

Combining the discussions of the isospin and spatial structure of the $K\bar{K}N$ system, we conclude that the structure of the $K\bar{K}N$ state can be understood simultaneous coexistence of $\Lambda(1405)$ and $a_0(980)$ clusters as shown in Fig. 1. This does not mean that the $K\bar{K}N$ system is described as superposition of the $\Lambda(1405)+K$ and $a_0(980)+N$ states, because these states are not orthogonal to each other. The probabilities for the $K\bar{K}N$ system to have these states are 90%. It means that $\bar{K}$ is shared by both $\Lambda(1405)$ and a_0 at the same time.

It is also interesting to compare the obtained $K\bar{K}N$ state with nuclear systems. As shown in Table 2, the hadron-hadron distances in the $K\bar{K}N$ state are about 2 fm, which is as large as nucleon-nucleon distances in nuclei. In particular, in the case (A), the hadron-hadron distances are larger than 2 fm and the r.m.s. radius of the three-body system is also as large as 1.7 fm. This is larger than the r.m.s. radius 1.4 fm of ^{4}He. If we assume uniform sphere density of the three-hadron system with the r.m.s. radius 1.7 fm, the mean hadron density is to be 0.07 hadrons/(fm^3). Thus the $K\bar{K}N$ state has large spatial extent and dilute hadron density.

We discuss the role of the KN repulsion in the $K\bar{K}N$ system. In Table 2, we show the results calculated without the KN interaction. We find in both (A) and (B) cases that the binding energy of the $K\bar{K}N$ state is 20 MeV larger than the case with the KN repulsion, and that the widths also becomes larger, $\Gamma = 130 - 140$ MeV. We also obtain smaller three-body systems as shown in Table 2. As a result of the localization, the system can gain more potential energy and larger imaginary energy in the case of no KN interaction than the case with the KN repulsion. In other words, thanks to the KN repulsion, the $K\bar{K}N$ state is weakly bound and its width is suppressed to be as small as the sum of the widths of the subsystems. The distances of the two-body subsystems are as small as about 1.5 fm, which is comparable with the sum of the charge radii of proton (0.8 fm) and K^+ (0.6 fm). For such small systems, three-body interactions and transitions to two particles could be important. In addition, the present picture that the system is described in nonrelativistic three particles might be broken down, and one would need relativistic treatments and two-body potentials with consideration of internal structures of the constituent hadrons.

Finally we shortly discuss the $\bar{K}\bar{K}N$ system with $S=-2$, $I=1/2$ and $J^p = (1/2)^+$. For the $\bar{K}\bar{K}N$ system, the binding energy from the $\Lambda(1405)+\bar{K}$ threshold is as small as a few MeV due to the strong repulsion $\bar{K}\bar{K}$ with $I=1$. The reason of the small binding energy is understood by isospin configuration of this system. Due to the strong attraction of $\bar{K}N$ with $I=0$, one of the $\bar{K}N$ pair forms a quesibound $\Lambda(1405)$ state. At the same time, the other pair of $\bar{K}N$ has dominantly $I=1$ component to have total isospin 1/2 of the $\bar{K}\bar{K}N$ system. Although the $\bar{K}N$ with $I=1$ is attractive, the attraction is not enough to overcome the repulsive $\bar{K}\bar{K}$ interaction.

4 Conclusion

We have investigated the $K\bar{K}N$ system with $J^p = 1/2^+$ and $I = 1/2$ in non-relativistic three-body calculation under assumption that $\bar{K}N$ and $K\bar{K}$ systems form quasibound states as $\Lambda(1405)$, $f_0(980)$ and $a_0(980)$. The present three-body calculation suggests a weakly quasibound state below all threshold of the two-body subsyetems. For the structure of the $K\bar{K}N$ system, we have found that, in the $K\bar{K}N$ state, the subsystems of $\bar{K}N$ and $K\bar{K}$ are dominated by $I=0$ and $I=1$, respectively, and that these subsystems have very similar properties with those in the two-particle systems. This leads that the $K\bar{K}N$ quasi-bound system can be interpreted as coexistence state of $\Lambda(1405)$ and $a_0(980)$ clusters, and $\bar{K}$ is a constituent of both $\Lambda(1405)$ and $a_0(980)$ at the same time. Consequently, the binding energy and the width of the $K\bar{K}N$ state is almost the sum of those in $\Lambda(1405)$ and $a_0(980)$, and the dominant decay modes are $\pi\Sigma K$ from the $\Lambda(1405)$ decay and $\pi\eta N$ from the $a_0(980)$ decay. The decays to $\pi\Lambda K$ and $\pi\pi N$ channels are suppressed. We also have found that the root-mean-square radius of the $K\bar{K}N$ state is as larger as 1.7 fm and the inter-hadron distances are larger than 2 fm. These values are comparable to, or even larger than, the radius of ^{4}He and typical nucleon-nucleon distances in nuclei. Therefore, the $K\bar{K}N$ system more spatially extends than typical hadronic systems. These features are caused by the weak binding of the three hadrons, for which the KN repulsive interaction plays an important role.

Acknowledgments: This work was partially supported by the Grant for Scientific Research (No. 18540263 and No. 20028004) from JSPS and MEXT and was done under the Yukawa International Project for Quark-Hadron Sciences (YIPQS). Computational calculations of this work were done by using the supercomputer at YITP.

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